INVESTIGATION ON DIFFERENT COMPOSITION OF POWDER METALLURGY ELECTRODE (Cu-W) IN HIGH PERFORMANCE EDM (HPEDM) ON AISI D2 HARDENED STEEL

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ABSTRACT

The ideal selection of manufacturing conditions is one of the most important aspects to take into consideration in the majority of manufacturing processes and particularly in processes related to Electrical Discharge Machining (EDM). EDM die sinking machines are used to machine conductive metals of any hardness or difficult to machine with traditional methods. The problem in the capabilities of tool electrodes which are not utilized at the optimum levels of the operating parameters has attracted the attention of researchers and practicing engineers to manufacture tool electrodes with highly great performance. In this work, an experimental design was conducted to characterize the machining performances and surface integrity of three different composition of copper tungsten (CuW) tool electrode in EDM of D2 hardened steel (58-62 HRC). Machining performances i.e. material removal rate (MRR), tool wear rate (TWR), workpiece surface roughness (Ra) and micro-hardness (MH) were studied for the three different composition of CuW tool electrode made through powder metallurgy (PM) method. Machining variables were peak current and pulse duration, meanwhile machining voltage, depth of cut and duty factor were kept constant. The 65%W electrode is the best choice of CuW electrode on machining D2 hardened steel due to the highest machining rate, reasonable tool wear rate and acceptable surface characteristics. The improvement of MRR is obviously affected by the increment of current intensity. MRR increased as the value of peak current increased. The increment of pulse duration is not essentially improving MRR. There is no clear relation between the alteration of pulse duration and MRR. However, the MRR becomes the optimum at an optimal set of variables which is set at 40A and 400μs. The results of the machining performance can extent the availability of database on EDM machinability and surface characteristics of D2 hardened steel for machinist practices in industrial application of roughing operation.

ABSTRAK

Pemilihan yang betul bagi penentuan pembuatan adalah salah satu daripada aspek paling penting untuk mengambil kira dalam kebanyakan proses pembuatan dan terutamanya dalam proses yang berkaitan dengan Mesin Pelepasan Elektrik (EDM). Mesin EDM penenggelaman acuan digunakan untuk memesin logam konduktif bagi sebarang kekerasan atau sukar untuk dimesin menggunakan kaedah tradisional. Masalah dalam keupayaan alat elektrod yang tidak digunakan pada tahap operasi parameter yang optimum telah menarik perhatian penyelidik dan pengamal jurutera untuk mengeluarkan alat elektrod yang berprestasi sangat baik. Dalam penyelidikan ini, reka bentuk eksperimen telah dijalankan untuk menciri prestasi pemesinan dan permukaan integriti tiga komposisi yang berbeza bagi tembaga tungsten (CuW) alat elektrod dalam EDM keluli dikeras D2 (58-62 HRC). Prestasi Pemesinan iaitu kadar pembuangan bahan (MRR), kadar kehausan alat (TWR), kekerasan permukaan bahan kerja (Ra) dan kekerasan-mikro (MH) telah dikaji menggunakan tiga komposisi yang berbeza bagi alat elektrod CuW yang dihasilkan melalui kaedah serbuk metalurgi (PM). Pembolehubah pemesinan iaitu puncak arus dan tempoh denyutan, manakala voltan pemesinan, kedalaman pemotongan dan faktor kerja adalah malar. Elektrod 65%W adalah pilihan terbaik bagi elektrod CuW untuk memesin keluli dikeras D2 kerana kadar pemesinan tertinggi, kadar munasabah kehausan alat dan ciri-ciri permukaan yang memuaskan. Peningkatan MRR jelas terjejas oleh kenaikan arus intensiti. MRR meningkat apabila nilai arus puncak meningkat. Kenaikan tempoh denyutan adalah pada asasnya tidak meningkatkan MRR. Tidak terdapat hubungan yang jelas antara perubahan tempoh denyutan dan MRR. Walau bagaimanapun, MRR menjadi optimum di set optimum pembolehubah yang disetkan pada 40A dan 400µs. Keputusan prestasi pemesinan boleh ditambah dalam pangkalan data bagi mesin EDM dan ciri-ciri permukaan keluli yang dikeras D2 untuk amalan pemesin untuk diaplikasikan dalam industri untuk operasi kekasaran.

CONTENTS

CHAPTER 1

INRODUCTION

Electrical discharge machining (EDM) has been extensively used in mould and dies industries. Classified as a one of thermal advanced machining process, EDM is able to machine hard material such as metal alloyed and hardened steels. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage in the manufacture of mould, die, automotive, aerospace and surgical components. Material removal rate is an important performance measure and several researchers explored several ways to improve it. Although most researchers tried to optimize process parameters to get optimum combination of performance measures for different work-tool interfaces but several researchers tried innovative ways of MRR improvement as well. The application of CNC to EDM has helped to explore the possibility of using alternative types of tooling to improve the material removal rate (MRR). The research work in the area of tooling design can be classified into two categories. First, by investigating suitable electrode material for a particular workpiece material and the second one is by trying different kind of electrode geometries and designs (Ojha et al., 2010). Earlier investigation showed that the combination of high electrical and thermal conductivity, high melting point and high wear resistance of EDM tool electrode is a basic requirement for high machining performance (Khanra et al., 2009). The basic requirement is vital to machine high hardness material i.e. hardened steel, titanium, tungsten carbide and inconel for prolonged machining. However, most single element tool electrode i.e. copper, graphite and brass are not fully satisfies the basic requirement. Therefore, research is going on to develop a composite material which satisfies the basic requirement of tool properties.

Tool wear process is similar to material removal mechanism as the tool and workpiece are considered as a set of electrodes in EDM. Some useful applications exploiting both the advantages and disadvantages of electrode wear have been developed. Marafona and Wykes (2000) introduced a wear inhibitor carbon layer on the electrode surface by adjusting the settings of the process parameters prior to normal EDM conditions. Although the thickness of the carbon inhibitor layer made a significant improvement on the tool wear rate (TWR) and it had little improvement on the MRR (Mohri et al., 2000).

Some researchers have made attempt to correlate the usefulness of powder metallurgy (PM) electrodes in EDM. Beri and Kumar, (2011) used an L18 orthogonal array with grey relation analysis to identify the effect of process parameters on the performance characteristics i.e., material removal rate, surface roughness and surface hardness. It is found that copper tungsten PM electrode gives better multi-objective performance than conventional copper electrode. Powder metallurgy electrodes are also found to be more sensitive to pulse current and pulse duration than conventional solid electrodes (Samuel and Philip, 1997). Hence, continuous research is required to explore the effective means by varying both pulse current and pulse duration in order to improve the performance of EDM process.

In the present investigation, three different compositions of copper tungsten (Cu-W) electrodes: 15% Cu - 85% W, 25% Cu – 75% W and 35% Cu – 65% W are used to machine AISI D2 hardened tool steel. Cu-W electrode possesses a combination of the high thermal and electrical conductivity of copper (Cu) and the minimal spark erosion (tool wear), a low thermal expansion coefficient, and the high melting temperature of tungsten (W). The low melting of copper increases the tool wear rate (TWR) and makes it necessary for another material with high melting point to be introduced. Materials having good electrical and thermal conductivity with a high meting point are preferably used in copper based electrodes to reduce electrode wear. The remarkable fact showed that tungsten has the highest melting point of all non-alloyed metals and the second highest of all the elements after carbon in periodic table. Therefore, tungsten is highly expected as a suitable material to be mixed together with copper in electrode fabrication in order to improve TWR. Tungsten has a melting point of about 3422°C which is slightly higher than the melting point of graphite (Gr). Melting point of graphite is about 3300°C and has very high level of thermal stability and also high heat resistance and therefore, graphite tool electrode normally used for high performance of metal removal in EDM machining process. However, graphite is not suitable to be used as an electrode for good surface finish of machined surface since graphite is brittle and has relatively porous surface. Lee et al. (2001) claimed that materials that require large amount of energy to melt usually have high melting temperature. The higher the melting temperature, the lower is the electrode wear whereby the melting point of 25% Cu - 75% W = 3500°C, graphite (Gr) = 3300°C and copper (Cu) = 1083°C. It was found that the electrode wear rate is inversely proportional to melting point of the electrode. Thus, the combination of copper and tungsten (Cu-W) which has the highest melting temperature and hence producing the lowest TWR is a keen interest in this study. As the high productivity of EDM which employing higher current and pulse duration is a most concern in manufacturing industry, thus it is indeed practical to explore the different composition percentage of copper tungsten in machining mold and die materials.

1.1 Background of Study

Fabrication of tool electrode is one of the most critical parts of the way to improve the performance of EDM process in terms of tool wear, production rate and surface quality of machined surface. The majority of work has been done using mechanically formed tool electrodes. However, due to their economical and technological disadvantages, EDM users are compelled to search alternative tooling. Tool made through powder metallurgy (PM) process not only offer overcoming of aforementioned challenges but also envisaged imparting desirable surface properties. A complex electrode made by a conventional method can cost around 100 times more than a simple square electrode (Beri et al., 2010). However, in the PM route a large number of tool electrodes can be made from a single die and punch assembly, resulting in an overall reduction of EDM tooling cost. Therefore, PM turns out to be a viable alternative to produce tool electrodes in which the desirable properties of different materials can be combined. In addition, the electrodes made through PM technology from special powders have an advantage to employ better machined surfaces of EDM process in recent years, to improve wear and corrosion resistance. Simao et al. (2003) claimed that EDM process may result in the increase of work surface micro hardness and improvement in wear resistance if hard materials like Ti, W, Cr, etc. are one of the constituents of the PM electrode. At the same time, PM electrode must be protected from wear during machining process. Marafona (2009) claims that tool wear rate (TWR) of an electrode decreased correspond to the increasing of carbon and chromium composition on the electrode machined surface. For this reason, three different composition of copper tungsten (Cu-W) made through powder metallurgy method are used as tool electrode in this study. The specimen of AISI D2 hardened tool steel with average hardness of 56-62 HRC, which is widely used in the mould and dies industry, is a target material in this study. AISI D2 hardened tool steel contains high carbon and high chromium which is capable to reduce TWR by depositing carbon layer on tool electrode surface during machining process. The surface morphology of electrode machined surface is analyzed by using scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS).

1.2 Problem Statement

Nowadays, EDM research has concentrated on achieving faster and more efficient material removal rate (MRR) coupled with a reduction in tool wear and improved surface characteristics. The usage of higher peak current and longer pulse duration result in higher material removal rate. At the same time, low tool wear ratio can also be satisfied because the carbon layer deposited on the electrode is thicker when longer pulse durations are used. However, longer pulse duration is not suitable to impart better surface roughness because large crater is generated by each pulse discharge. Thus, this pulse condition is normally used in rough machining.

In high performance EDM, higher machining rate is significantly require to improve productivity rate by reduction of lead time. The problem acquire for an electrode to improve machining rate are low melting point, poor thermal and electrical conductivity. Copper is a primary electrode material used in most manufacturing industries involving EDM process due to their tool-making culture that is averse to the untidiness of working with graphite. However, copper electrodes will generally burn workpiece surface only half as fast as graphite electrodes. Copper is a ductile metal with very high thermal and electrical conductivity. Low melting point of copper required any other conductive material to be introduced to mix together with copper to become a great electrode. Of all metals in pure form, typical tungsten has the highest melting point (3,422 °C) and lowest vapor pressure at temperatures above 1,650 °C. The low thermal expansion and high melting point and strength of tungsten originate from strong covalent bonds formed between tungsten atoms. Tungsten is a hard steel-gray metal that is often brittle and hard to work. If made very pure, tungsten retains its hardness which exceeds that of many steels, and becomes malleable enough that it can be worked easily. Therefore, tungsten becomes one of the best metal selections to be mix together with copper in order to be as a tool electrode.

Copper tungsten materials are composites of tungsten and copper. In this research, they are produced through powder metallurgy process. Copper tungsten is very expensive compared to other electrode materials, but is useful for making deep slots under poor flushing conditions and in the EDM machining of tungsten carbide and hardened tool steel. Therefore, investigation on different composition of copper and tungsten in CuW electrodes is really required in order to determine their performance and machinability in EDM process.

The type of workpiece material also play important role to improve TWR during machining process. High amount of carbon content in work material is highly believed can improve TWR. The improvement can be done by the decomposition of carbon element from work material through dielectric fluid then deposited onto the tool electrode surface. The hydrocarbon dielectric i.e. kerosene also contain carbon element which can be deposited on the tool electrode. TWR reduce by the increasing of equivalent carbon deposited on the tool electrode. The increase of equivalent carbon in the black layer composition decreases the thermal conductivity of the electrode surface contributing to TWR improvement. Therefore, high carbon contain of workpiece material play decisive role to reduce TWR in order to improve EDM performance.

1.3 Objectives

The aim of the research is to investigate the effect of cutting variables of different percentage composition of copper tungsten (CuW) electrode on the following criteria:

i. Machinability:

- a) Tool electrode wear rate.
- b) Material removal rate.
- c) Workpiece surface roughness.

ii. Surface integrity:

- a) Tool electrode wear morphology.
- b) Workpiece surface topography.
- c) Subsurface layer changes which includes recast layer (white layer) and heat affected zone (HAZ).
- d) Micro hardness at deeper layer of the machined surface.

1.4 Scope

The scope of the research:

i. Using a *Sodick AQ55L* EDM die-sinking machine to carry out the experiments designed.

ii. The main parameters investigated are peak current and pulse duration whereby discharge voltage, pulse interval, polarity and other parameters are kept constant.

iii. Powder metallurgy tool electrode (CuW: Copper-Tungsten) is selected as the cutting tool of machining the work piece. Three different composition of CuW; 15% Cu - 85% W, 25% Cu – 75% W and 35% Cu – 65% W are used throughout this study.

iv. Conducting the machining operation on AISI D2 hardened steel (having a typical hardness range of 56-62 HRC) as work material.

v. The experiment is carried out in hydro-carbon oils (i.e. kerosene) as a dielectric medium.

vi. Conducting experimental trials to investigate and evaluate the following responses:

a) Tool electrodes wear rate by Digital Weighing Machine.

b) Tool electrodes wear morphology by SEM.

c) Material removal rate by Digital Weighing Machine.

d) Workpiece surface roughness using Surface Profiler.

e) Workpiece surface topography using Scanning Electron Microscope (SEM).

f) Subsurface layer changes which includes recast layer (white layer) and heat affected zone (HAZ) using Field Emission Scanning Electron Microscope (FE-SEM).

g) Microhardness at deeper layer of the machined surface using Vickers Hardness Tester.

vii. Analyzing data of gathered through experiments with:

a) Observation of machining characteristics of the workpiece materials due to the surface integrity.

b) Evaluation and comparison of the effect of cutting conditions on the machinability of the cutting tool material with the effects of workpiece surface integrity or alteration.

5 Significance of study

The investigation on different composition of powder metallurgy electrode of CuW in high performance EDM (HPEDM) of AISI D2 hardened steel leads to the development of high performance machining process of EDM die sinking. This research has concentrated on achieving faster and more efficient metal removal rate (MRR) coupled with reasonable improvement in tool wear and surface characteristics. Three different composition of powder metallurgy electrode of CuW (15% Cu - 85% W, 25% Cu – 75% W and 35% Cu – 65% W) are used as tool electrode to obtain the most optimum performance among them. The most optimum performance electrode contributes to the industrial development by satisfying economical objective of maximizing production rate and minimizing production cost due to high material removal rate and low tool wear rate. This research also investigates and evaluates surface integrity and morphology of both tool and workpiece images scan using FE-SEM.

1.6 Hypothesis

Tool performance is one of the important factors that determine the quality of the machined component. Based on the investigation on machining performance of different composition of powder metallurgy (PM) electrode of copper tungsten (CuW) which can lead to determine the best performance of tool electrode in machining D2 hardened steels for high productivity machining process in EDM die sinking operation. High performance tool electrode can help to improve machining capability to remove efficiently material from workpiece material. The highest performance tool electrode may contribute to the development of mould and die industries.

This research concentrates on high productivity machining process by achieving faster and more efficient metal removal rate (MRR) by using higher peak current and pulse duration without compromising of tool wear rate (TWR) and surface characteristics. Furthermore, the advantages of PM electrode which has low tooling cost and impart desirable properties of tool electrode by combination of different materials which hopefully satisfy the economical objective of optimizing machining rate and cost.

The evaluation of surface morphology and surface integrity scan images using SEM and FE-SEM will give good information about surface structures and characteristics of both tool and workpiece. The information will be used to analyze wear morphology of tool electrode and surface integrity of workpiece machined surface.

CHAPTER 2

THE FUNDAMENTAL OF ELECTRICAL DISCHARGE MACHINING (EDM)

The electrical discharge machining (EDM) phenomenon was first noticed about the year 1700. Soon after this, Benjamin Franklin wrote of witnessing "the actual removal of metal by electrical sparks." In 1881, Meritens first used arcs for welding. However, it was not until around 1948, that Lazarenkos, a Russian husband and wife team, first applied the principle to a machine for metal stock removal. The popularity of this machining method has grown by leaps and bounds since 1970. Lately, its growth rate has been about 30% annually (Brown, 1998). Machine power, speed of stock removal, and types of jobs EDM can do better than any other machining method have increased to the point that many jobs must now be done by EDM in order to be competitive.

2.1 Introduction

EDM is categorized as a thermal advanced machining process, hard materials such as quenched steel, cemented carbide and electrically conductive ceramics can be machined. The hardness of the workpiece has no effect on the process. The material could be hardened tool steel or even carbide. Rather than machine a part before heat treating it, EDM permits the machining to be done after hardening. This eliminates risk of distortion or any other damage. EDM also allows machining of intricate shapes. Since the tool electrode does not need to rotate for material removal like milling or grinding, holes with sharp corners and irregular contours can be machined without difficulty. Reaction forces generated in the EDM gap are insignificant, which also facilitates the machining of thin and flexible parts, and deep grooves and holes which are difficult to machine by milling.

The workpiece can be formed, either by replication of a shaped tool electrode, or by 3D movement of a simple electrode like in milling or a combination of the above. The electrode material is normally copper or graphite. Figure 2.1 shows a schematic diagram of EDM die sinking. The numerical control (NC) monitors the gap condition of voltage and current and synchronously controls the different axes and the pulse generator. The dielectric liquid is filtrated to remove debris particles and decomposition products. In EDM die sinking, hydrocarbons dielectric are normally used as dielectric medium for better surface roughness (R_a) and give lower tool wear rate (TWR) compared to de-ionized water (Wong et al., 1995).

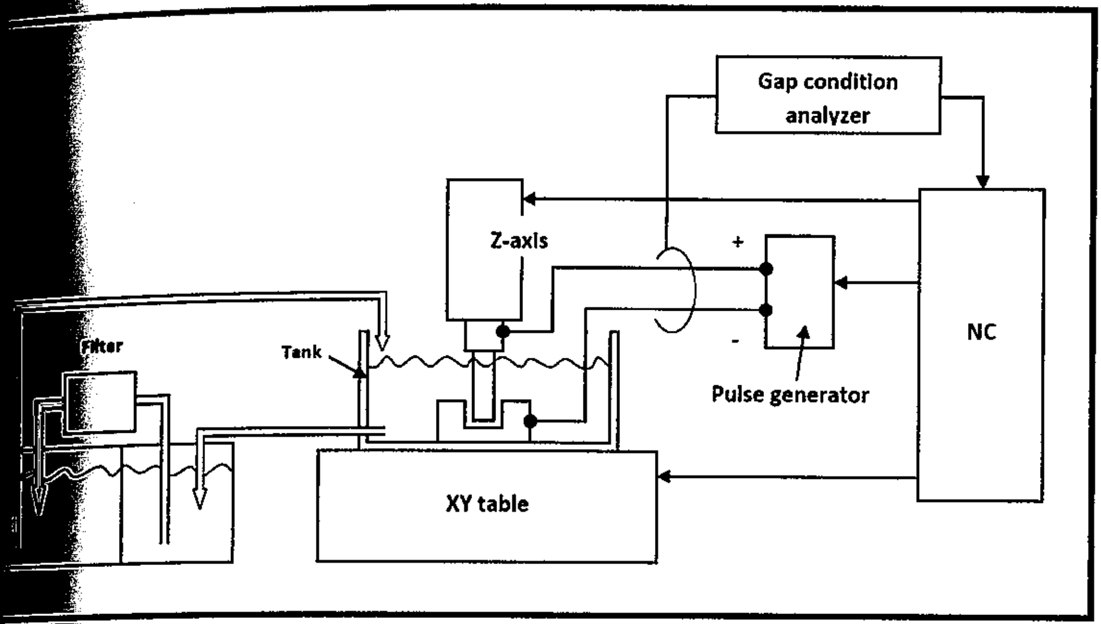

Figure 2.1: Schematic diagram of EDM die sinking machine.

EDM is a precision metal removal process using an accurately controlled electrical discharge (spark) to erode metal. This process will machine any electrically conductive metal, regardless of its hardness. Figure 2.2 shows the concept of EDM die sinking. Pulsed arc discharges occur in the gap filled with an insulating medium, preferably a dielectric fluid like hydrocarbon oil between tool electrode and workpiece. The insulating effect of the dielectric medium has some importance in avoiding electrolysis effects on the electrodes during an EDM process. To visualize the process, picture one electric spark passing from a positively charged (+) electrode to a negatively charged (-) workpiece and both of them immersed in the same bath of dielectric oil. The energy of the spark brings particles of the workpiece to a vaporized state. These particles immediately resolidify into small spheres and are flushed away by the dielectric oil, leaving a small pocket eroded in the workpiece. This cycle, repeated thousands of times each second, erodes material from the workpiece until a reverse image of the electrode is formed in the workpiece.

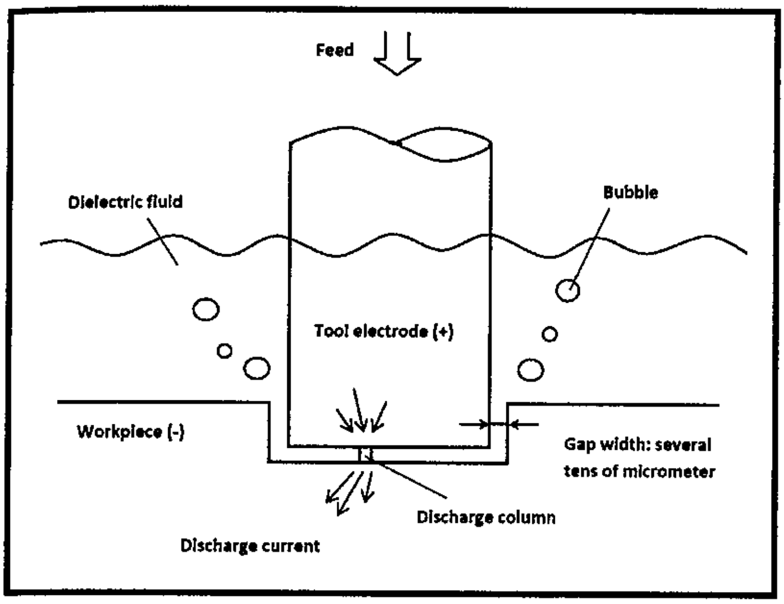

Figure 2.2: Concept of EDM die sinking.

The EDM machined cavity will always be larger than the electrode. The electrode is always made slightly smaller than the cavity desired because the erosive action progressing outward from the electrode always produces a cavity slightly larger than the electrode. The difference between the electrode and the workpiece gap is called the *overcut*. The amount of overcut will vary according to the amount of current, pulse on/off time, type of electrode, and workpiece materials. Once established, overcut is predictable.

High machining rates are proportional to high current. However, high amperage generally requires large machining areas, and provides rough surface finishes. Fifty amps per square inch can normally be applied to graphite electrodes when roughing areas larger than 0.5 square inches. Copper electrodes will take as much as sixty amps per square inch (Sommer, 2009). Electrode wear is at minimum under heavy stock removal conditions. When considering finish removal rates, the amperage, and, consequently, the stock removal rate is limited by required finish. Fine finishes are possible only at low amps, which create faster electrode wear. So, the finer the required finish, the slower the machining rate and the greater the electrode wears. That is why it is often more desirable and economical to finish and polish the workpiece off the EDM machine, rather than try to achieve a high finish through the processes. It is advised that you avoid extra fine finishes in the process unless specifications shape demand it.

Most dies and molds for any use can be made inexpensively by EDM. That includes but is not restricted to molds for the plastic industry, powder metallurgy, coining, stamping, forging, cold heading, extrusions, or dies casting. Generally, EDM these dies and molds are save time and money.

2.2 EDM machining parameters

The machining parameters and performance measures are shown in Figure 2.3. The machining parameters can be divided into two categories i.e. electrical and non-electrical parameters. Both categorized parameters play important role to improve machining performance. Good understanding about operating the machining parameters can optimize the machining performance. The performance measures in EDM machining can be divided into two categories i.e. qualitative and quantitative. In EDM, qualitative is focus on the quality of workpiece (product) surface after machining process. The performance measures are surface roughness and micro hardness of workpiece machined surface. Consequently, quantitative is more focus on machining rate and tool wear rate. Both machining performance measures are very important for high productivity machining and cost savings. All description about machining parameters and performance measures will be described in the next sub chapter.

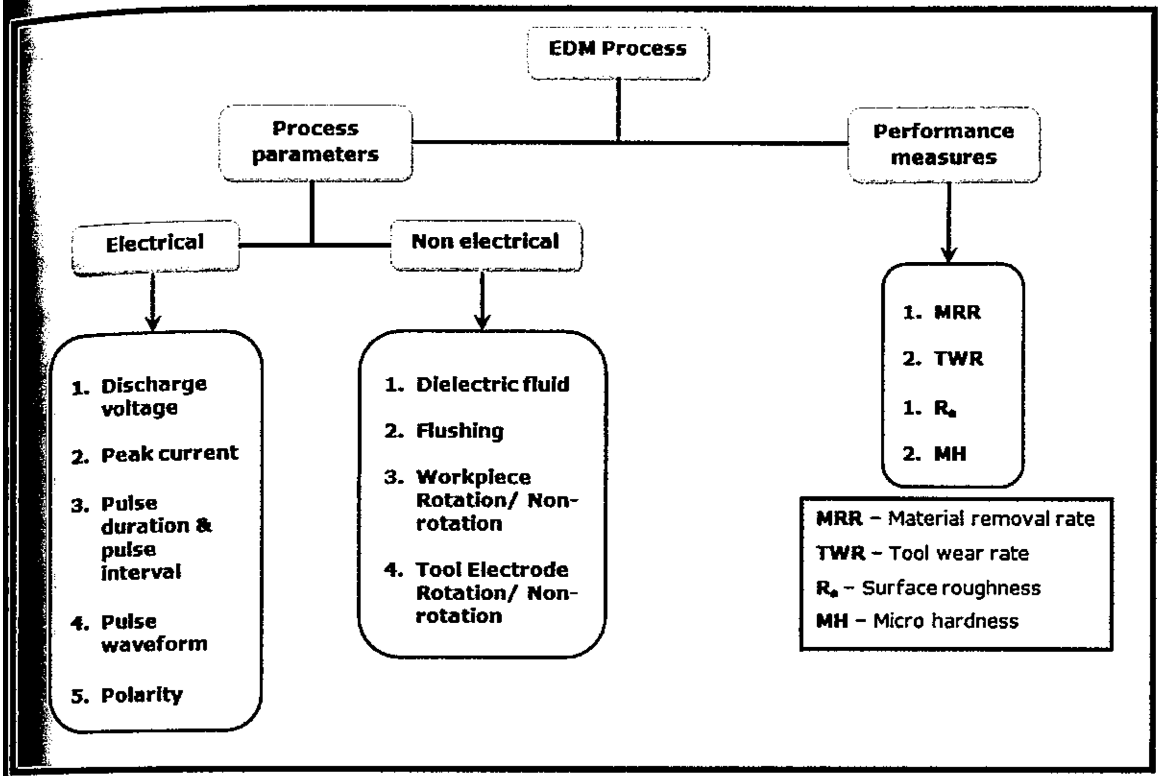

Figure 2.3: Process parameters and performance measures of EDM process.

2.2.1 EDM Electrical Parameters

Major electrical parameters are discharge voltage, peak current, pulse duration and pulse interval, pulse waveform and polarity. The EDM process is a stochastic thermal nature having complicated discharge mechanism. Therefore, it is difficult to explain all the effect of these parameters on performance measures. However, researchers now rely on process analysis for optimization of parameters to identify the effect of operating variables on achieving the desired machining characteristics. For an example, Lin et al. (2002) applied grey relational analysis for solving the complicated interrelationships between process parameters and the multiple performance measures. Taguchi approach has also been used by many other researchers to analyze and design the ideal EDM process (Tzeng and Chen, 2003).

2.2.1.1 Discharge voltage, V

Discharge voltage in EDM is related to the spark gap and breakdown strength of the dielectric (Kansal et al., 2005). Before current can flow, the open gap voltage increases until it has created an ionization path through the dielectric. Once the current starts the flow, voltage drops and stabilizes at the working gap level. The preset voltage determines the width of the spark gap between the leading edge of the electrode and workpiece. Higher voltage settings increase the gap, which improves the flushing conditions and helps to stabilize the cut. Material removal rate (MRR), tool wear rate (TWR) and surface roughness (R_a) increases, by increasing open circuit voltage, because electric field strength increases. However, the impact of changing open circuit voltage on surface hardness after machining has been found to be only marginal.

2.2.1.2 Peak current, I_p

This is the amount of power used in discharge machining, measuring in units of amperage, and is the most important machining parameter EDM. During each on-time pulse, the current increases until it reaches a preset level, which is expressed as the peak current. The maximum amount of amperage is governed by the surface area of the cut. Higher amperage is used in roughing operations and in cavities or details with large surface areas. Higher current will improve MRR, but at the cost of surface finish and tool wear. This is all more important in EDM because the machined cavity is a replica of tool electrode and excessive wear will hamper the accuracy of machining. New improved electrode materials, especially graphite, can work on high currents without much damage (Ho and Newman, 2003). Plotting voltage and current as a function of time gives a more detailed picture in Figure 2.4 which indicates (a) ionization time, (b) discharge time, (c) deionization time and (d) idle time.

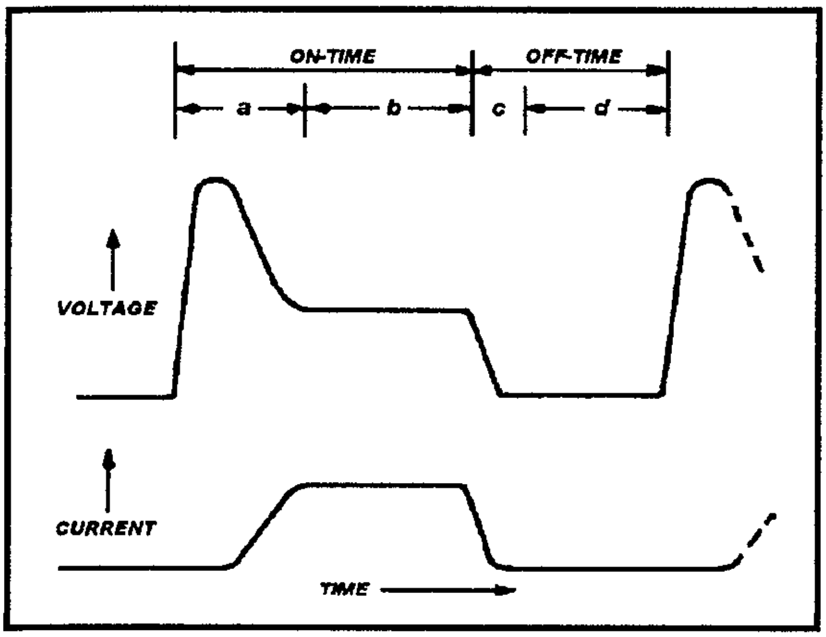

Figure 2.4: Actual profile of a single EDM pulse (Fuller, 1996).

2.2.1.3 Pulse duration (τ_{on}) and pulse interval (τ_{off})

Each cycle has an on-time (τ_{on}) and off-time (τ_{off}) that is expressed in units of microseconds (µs). Since all the work is done during on-time, the duration of these pulses and the number of cycles per second (frequency) are important. Metal removal is directly proportional to the amount of energy applied during the on-time (Singh et al., 2005). This energy is controlled by the peak amperage and the length of the on-time. Pulse on-time is commonly referred to as pulse duration and pulse off-time is called pulse interval. With longer pulse duration, more workpiece material will be melted away. The resulting crater will be broader and deeper than a crater produced by shorter pulse duration. These larger craters will create a rougher surface finish. Extended pulse duration also allow more heat to sink into the workpiece and spread, which means the recast layer will be larger and heat affected zone will be deeper.

However, excessive pulse duration can be counter-productive. When the optimum pulse duration for each electrode and work material combination is exceeded, material removal rate starts to decrease. A long duration can also put the electrode into a no-wear situation. Once that point is reached, increasing the duration further causes the electrode to grow from plating build-up. The cycle is completed when sufficient pulse interval allowed before the start of the next cycle. Pulse interval will affect the speed and stability of the cut. In theory, the shorter the interval, the faster it will be the machining operation. But if the interval is too short, the ejected workpiece material will not be swept away by the flow of the dielectric and the fluid will not be deionized. This will cause the next spark to be unstable. Unstable conditions cause erratic cycling and retraction of the advancing servo. This slows down cutting more than long, stable off-times. At the same times, pulse interval must be greater than the deionization time to prevent continued sparking at one point (Fuller, 1996). Modern power supplies allow independent setting of pulse on-times and off-times. Typical ranges are from 2 to 1000 µs. In ideal conditions, each pulse creates a spark. However, it has been observed practically that many pulses fail if duration and interval are not properly set, causing a loss of the machining efficiency. Such pulses are known as "open pulses".

In conclusion, on-time is the actual cutting time when workpiece disintegration is occurring. Off-time is the time provided to clear the disintegrated particles from the gap between the electrode and the workpiece. Both on-time and off-time are important. The on-time is set together with the amperes to establish metal removal rate, overburn, and surface finish. The off-time and flushing keep the cut clean, which is necessary for efficient stock removal.

2.2.1.4 Pulse waveform

The pulse waveform is normally rectangular, but generators with other pulse waveform have been also developed. Using a generator which can produce trapezoidal pulses, Bruyn (1968) succeeded in reducing relative tool wear to very low values. Other types of generators introduce an initial pulse of high voltage but low current and of a few microseconds duration, before the main pulse, which facilitates ignition. Figure 2.5– 2.7 depicted ideal EDM waveforms which are much simplified at different frequencies, and representative effects upon finish. As you can see in Figure 2.5, the finish left by long on-times is quite rough. This is because the long duration of the spark is sufficient enough to allow a great deal of heat to sink into the workpiece, melting a large crater, rather than vaporizing a small one. In addition the recast layer will be considerably thicker with a potentially deep heat affected zone (HAZ). This can present problems with the surface integrity of the part unless stock is left for removal by secondary finishing operations i.e. ECM (Electrical Chemical Machining), AFM (Abrasive Flow Machining), or manual polishing.

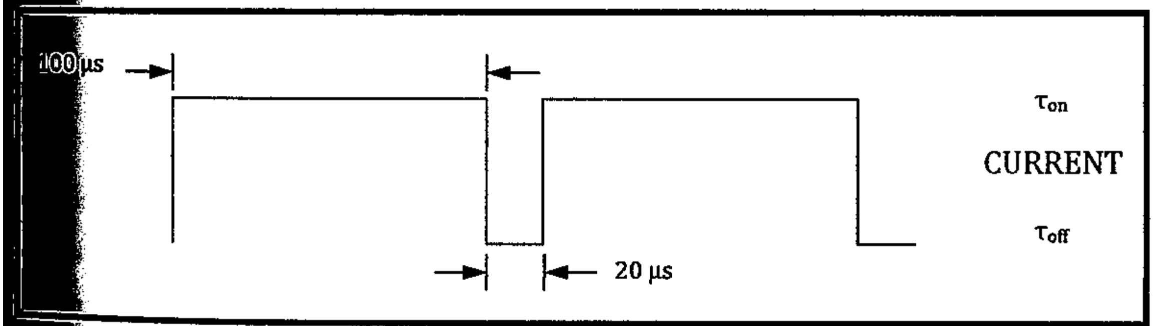

Figure 2.5: Low-frequency/roughing.

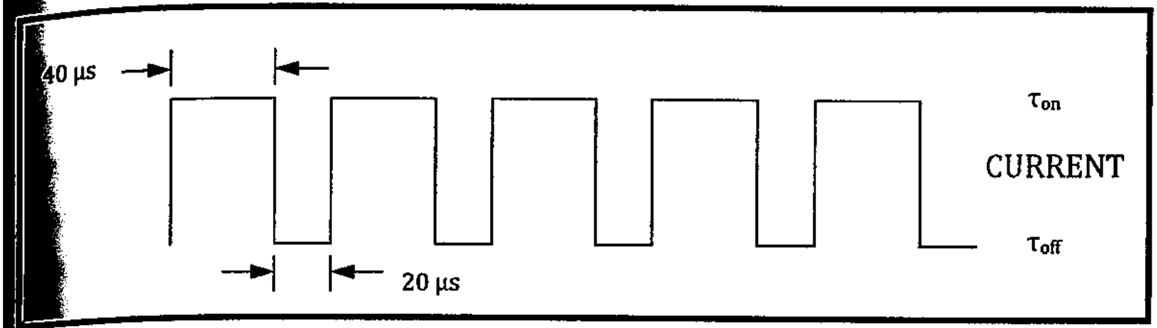

Figure 2.6: Moderate-frequency/semi-roughing.

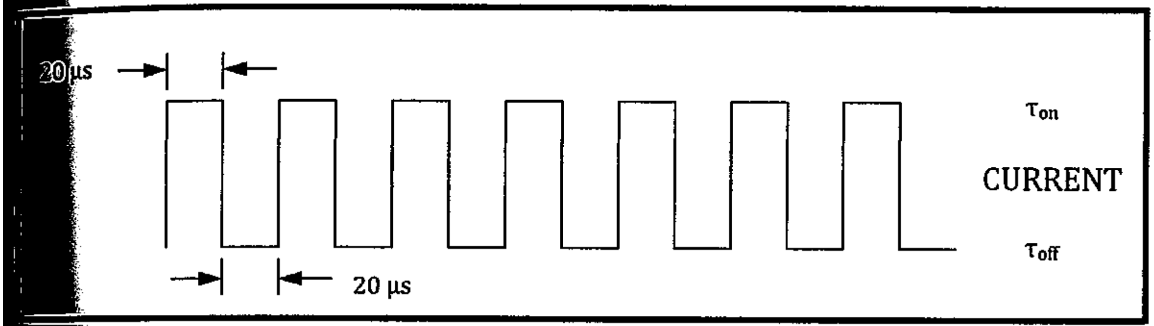

Figure 2.7: High-frequency/finishing.

2.1.5 Polarity

The polarity of the electrode can be either positive or negative. The current ...ing through the gap creates high temperature causing material evaporation at both ...ctrode spots. The plasma channel is composed of ion and electron flows. As the ...ctron processes (mass smaller than anions) show quicker reaction, the anode material ...worn out predominantly. This effect causes minimum wear to the tool electrodes and ...omes of importance under finishing operations with shorter on-times. However, ...le running longer discharges, the early electron process predominance changes to ...tron process (proportion of ion flow increases with pulse duration), resulting in high ... wear. In general, polarity is determined by experiments and is a matter of tool ...rial, work material, current density and pulse length combinations. Figure 2.8

shows the machining condition of EDM polarity. The polarity is depending on the machining conditions and material combination of the workpiece and the electrode, it may be necessary to change the polarity. If a polarity is set wrongly, good machining performance may not be obtained. A problem may be arising in electrode wear, machining speed, or arc resistance. Therefore, good information about choosing a suitable polarity from previous researchers is very importantly required. Table 2.1 shows the possible electrode polarity for different workpiece and tool combinations.

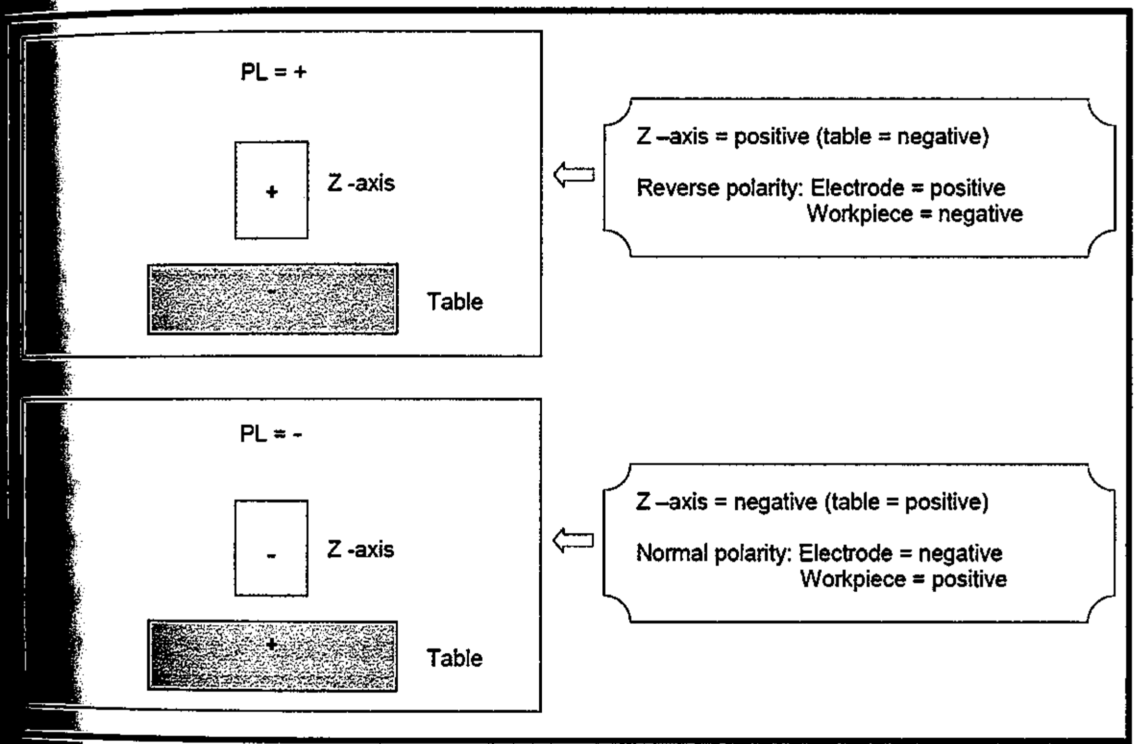

Figure 2.8: Machining condition of EDM polarity.

Table 2.1: Electrode polarities for different workpiece materials (El-Hofy, 2005)

Electrode material	Steel	Tungsten carbide	Copper	Aluminum	Ni-base alloys
Graphite	+, –	–	–	+	+, –
Copper	+	+, –	–	+	+
Cu-W	+	+, –	–	+	+
Steel	+, –	+	–	–	–
Brass	–	–		+	–

2.2 EDM non-electrical parameters

Main non-electrical parameters are flushing of dielectric, workpiece rotation/non-rotation and electrode rotation/non-rotation. These non electrical parameters play a critical role in optimizing performance measures. Researches on flushing pressure reveal that it affects the surface roughness, tool wear rate, acts as coolant and also plays a vital role in flushing away the debris from the machining gap (Lonardo, 1999). Workpiece rotary motion improves the circulation of the dielectric fluid in the spark gap and temperature distribution of the workpiece yielding better MRR and surface roughness (Guu and Hocheng, 2001). Similarly, electrode rotation results in better flushing action and sparking efficiency (Soni and Chakraverty, 1994). Therefore, improvement in MRR and surface roughness has been reported due to effective gap flushing by electrode rotation (Yan et al., 2000).

2.1 Dielectric fluid

The main requirements of the EDM dielectric fluids are adequate viscosity, high point, good oxidation stability, minimum odor, low cost, and good electrical arge efficiency. For most EDM operations kerosene is used with certain additives prevent gas bubbles and de-odorant. Silicon fluids and a mixture of these fluids petroleum oils have given excellent results. Other dielectric fluids with a varying ee of success include aqueous solutions of ethylene glycol, water in emulsions, and lled water. The main functions of the dielectric fluid are to flush the eroded cles (debris) from the machining gap. Furthermore, dielectric fluid provides lation between the electrode and the workpiece and also cools the section that was ed by the discharging effect. The dielectric must be constantly filtered, cooled and rculated. A great deal of heat is generated during the EDM process and the ectric absorbs the most of it. Additionally the process creates a lot of debris and this d to be filtered out of the system. As mentioned the dielectric fluid acts as an lator between the electrode and the mold cavity. There are many dielectrics to ose from based on the insulation properties of the fluid. Air is not a very good lator. Water is best. But water has a few drawbacks. First, it causes rust. Second, electrical discharge separates the water into pure hydrogen and pure oxygen and ome very explosive pair. A good compromise then is kerosene. No rust problem and angerous gasses are produced with kerosene.

Flushing

Flushing of the dielectric plays a major role in the maintenance of stable machining and the achievement of close tolerance and high surface quality. Inadequate flushing can result in arcing, decreased electrode life, and increased production time. Flushing also brings fresh dielectric oil into the gap and cools the electrode and the workpiece. The deeper the cavity cause greater difficulty for proper flushing.

Improper flushing causes erratic cutting. This in turn increases machining time. Under certain machining conditions, the eroded particles attach themselves to the workpiece. This prevents the electrode from cutting efficiently. It is necessary to remove the attached particles by cleaning the workpiece. The danger of arcing in the gap also exists when the eroded particles have not been sufficiently removed. Arcing occurs when a portion of the cavity contains too many eroded particles and the electric current passes through the accumulated particles. This arcing causes an unwanted cavity or cavities which can destroy the workpiece. Arcing is most likely to occur during the finishing operation because of the small gap that is required for finishing. New power supplies have been developed to reduce this danger.

There are four types of flushing i.e. pressure, suction, external, and pulse flushing. Each EDM process needs to be evaluated to choose the best flushing method. Pressure flushing also called injection flushing is the most common and preferred method for flushing. One great advantage of pressure flushing is that the operator can visually see the amount of oil that is being used for flushing. With pressure gauges, this method of flushing is simple to learn and use. Pressure flushing may be performed in two ways i.e. through the electrode or through the workpiece as shown in Figure 2.9.

REFERENCES

Ahsan, A.K., Mohammad Y.A. and Md. Mohafizul H., (2009). A study of electrode shape configuration on the performance of die sinking EDM. Int J Mech & Mat Eng (IJMME), Vol. 4, No.1, 19 - 23.

Altpeter, F., Perez, R., (2004). Relevant Topics in Wire Electrical Discharge Machining Control, J. of Materials Processing Technology, Vol. 149, Issues 1-3, 147 - 151.

Angelo, P.C., (2008). Powder Metallurgy: Science, Technology and Application; Prentice-Hall of India, 487 pp.

Bayramoglu, M., Duffill, A.W., (1995). Manufacturing linear and circular contours using CNC EDM and frame type tools. Int. J. Mach. Tools Manuf., 35(8), 1125–1136.

Beri, N. and Kumar, A., (2011). Optimisation of electrical discharge machining process with CuW powder metallurgy electrode using grey relation theory. International Journal Machining and Machinability of Materials, Vol. 9, Nos. 1/2.

Beri, N., Maheshwari, S., Sharma, C. and Kumar, A., (2008). Performance Evaluation of Powder Metallurgy Electrode in Electrical Discharge Machining of AISI D2 Steel Using Taguchi Method. International Journal of Aerospace and Mechanical Engineering 2:3, 167 – 171.

Beri, N., Maheshwari, S., Sharma, C. and Kumar, A., (2010). Technological Advancement in Electrical Discharge Machining with Powder Metallurgy Processed Electrodes: Review. Material and Manufacturing Processes, 25: 1186 – 1197.

Bley, P., Kruth, J.P., Lauwers, B., Schacht, B., Balasubramaniam, V., Froyen, Ludo. and Van Humbeeck, J.V., (2006). Surface and Sub-Surface Quality of Steel after EDM. Advanced Engineering Materials, 8, No. 1-2.

Brown, J., (1998). Advanced Machining Technology Handbook. New York: McGraw-Hill.

Davim, J.P., (2008). Machining: Fundamentals and Recent Advances. London: Springer.

Davim, J.P., (2011). Machining of Hard Materials. London: Springer.

Ekmekci, B., (2009). White Layer Composition, Heat Treatment, and Crack Formation In Electrical Discharge Machining Process. Metallurgical and Materials Transactions B, 40 (1), 70-81.

Fuller, John E., 1996. Electrical Discharge Machining. ASM Machining Handbook, vol. 16, pp. 557–564.

German, R., (2004). A-Z of Powder Metallurgy. Elsevier Science Publication, 5 pp.

Guu, Y.H., Hocheng, H., (2001). "Effects of workpiece rotation on machinability during electrical discharge machining", Journal of Material and Manufacturing Processes, 16 (1), 91–101.